TWENTYFIFTH EUROPEAN ROTORCRAFT FORUM

Paper n D7

THE MODERN HELICOPTER DESIGN CRISIS. ITS DISTINGUSHING FEATURES, CAUSE AND DEVELOPMENT

BY

THE CIBERNATIC INSTITUTE OF NAS OF UKRAINE

SEPTEMBER 14-16, 1999
ROME
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFESA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

I. Introduction.

The analysis of helicopter industry for last 50 years, i.e. from time of occurrence of the first generation of helicopters and beginning of their practical application, result in that unfavourable conclusion, that now rates of development of the given area of engineering considerably have decreased, it is possible even to speak about its begun degradation.

Speaking about the analysis, the author of the report means the not traditional analysis of statistics helicopter industry, and system historical-scientific analysis. The traditional analysis, which among other things seldom covers more than 10-15 years, would show certain growth of the majority of parameters of the aircraft, that could create impression of steady progress helicopter industry, while the historical-scientific analysis with sufficient evidence speaks, that this impression is deceptive. The historical-scientific research has other methodological basis and pursues other purposes, it examines object not by itself, and in interaction with other objects and phenomena, in which environment it arises, develops, functions. The purpose of such research to define the forms, logic and laws of development of object to find system of the factors, causing them, and also to establish, as the named system functions. (When the question is designing, which is the creative process initially focused on the account " of social aspect of the received result realisation "[1], the researching object is examined in interaction with social environment.)

Such tasks can not be solved, if the analysis covers only separate historical piece of life of the object, - it is necessary to consider its development during all time of its existence from the moment of origin of idea.

In due time author has carried out detailed multidimensional research of such kind which has captured all history of helicopters design up to middle of the 1980-Th. years [2]. By continuing it in some aspects till now, he has come to the above mentioned conclusions. Some of the received results are stated in the given report, they should be considered as preliminary, they will be specified in process of a deepening of the research and the increases of quantity of the used information (today's opportunities of the author in this respect objectively are limited). However and the received picture gives rather clear idea about a modern condition of helicopter industry, and also about the nearest prospects of its development.

The specified analysis is carried out in frameworks of wider research in the field of methodology of systems designing, which is carried out now in The Cybernetics Institute of NAS of Ukraine. In case of successful end it will allow not only to explain the reasons of the generated crisis in helicopter industry, but also to find ways of an output from it.

II. Features of modern crisis in the helicopter industry.

In the brief generalised form the essence of a today's situation in the helicopter industry can be formulated as follows: *a helicopter ceases to correspond to the public role.* Any technical system, especially vehicle, is a part of public life, and the requirements to it reflect public need for the given technical system, and concerning quality of performance its particular purposes by it, and concerning its ability to be entered in bio- and technosphere, not putting them damage. During public development under influence of a number of the factors the requirements change [2,3].

In methodology of designing requirements to system generated by public development and reflecting practical need for it, are determined as *the goal of its designing* [f.ex.4,5], or the fore seeing greatest possible effect [4, p.26]. In this case we consider purpose of designing of not concrete particular variant, and all given class of systems. If in required system this purpose is not realised, depending on a degree of a divergence of parameters of system with the requirements, or the interest of a society to it is reduced, or the system in general can be thrown out from public life as useless or even harmful. Just it has taken place in due time with dirigible balloons and autojiros.

To answer on question, in what condition is helicopter industry today, the author has analysed the modern goal of designing, and also the most specific characteristics of the newest helicopters and has compared them. In result the following picture has turned out.

General goal of helicopters design, as the earlier carried out historic-scientific analysis [2], has shown at an initial qualitative level was completely generated in 1970s . Since that time it includes three basic groups of the requirements: functional - technical, economic, ecological. Naturally, inside each of groups the development of the requirements proceeds and qualitatively and quantitatively. In Fig.1 most convenient for tasks of our research graphic model of the design goal is shown, i.e. constructed with appropriate by the character and degree of detailed elaboration.

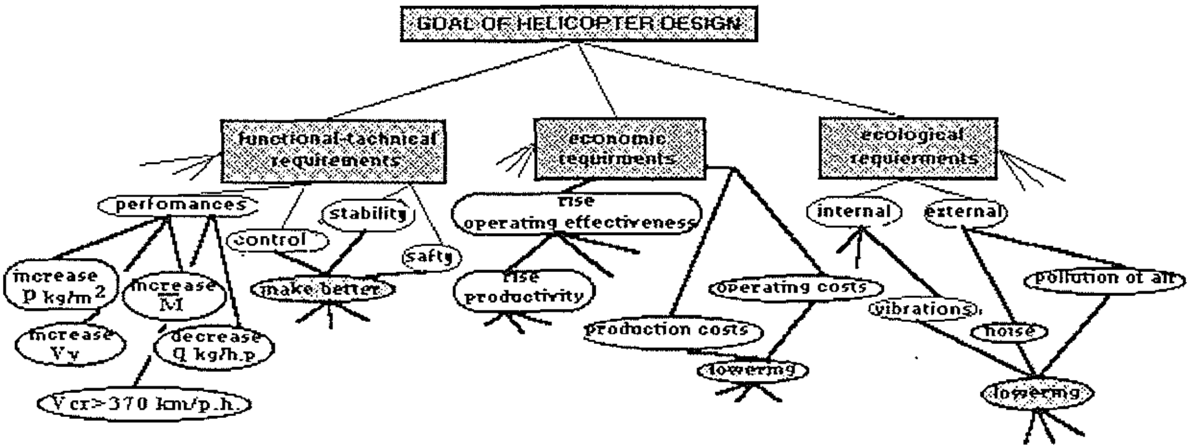


Fig.1. The Model of Helicopter Design Goal

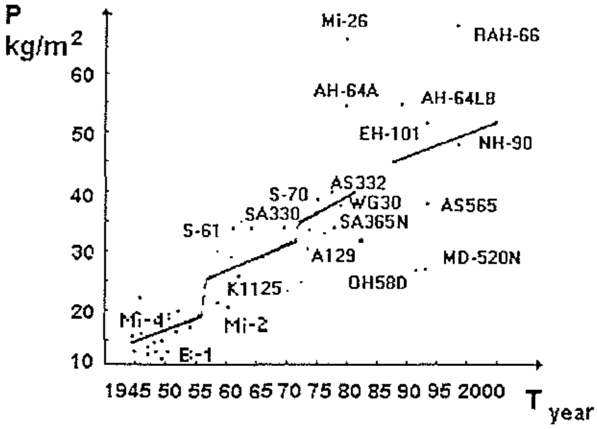
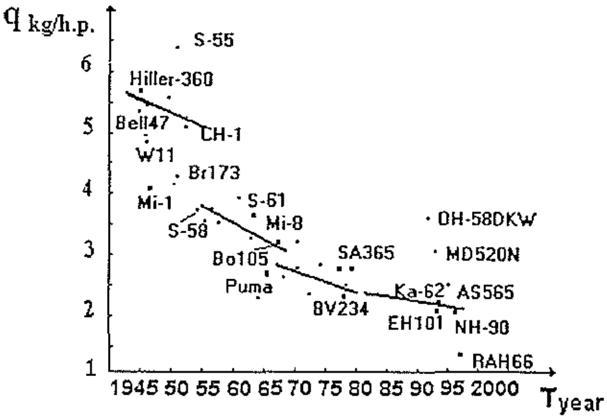


Fig.2



Fig,3

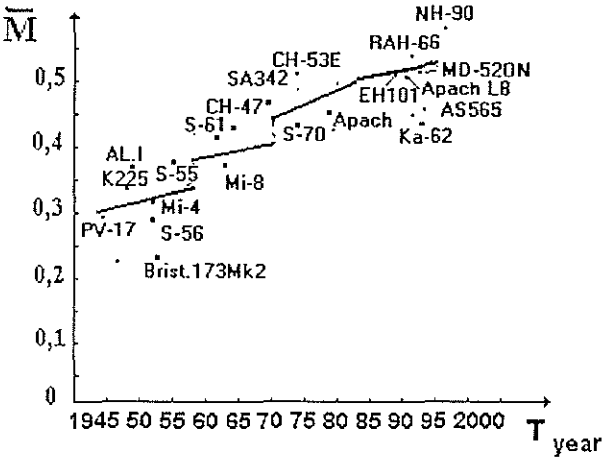


Fig.4

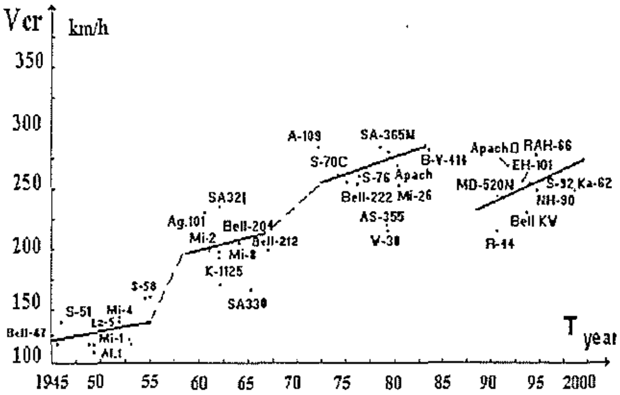


Fig.5

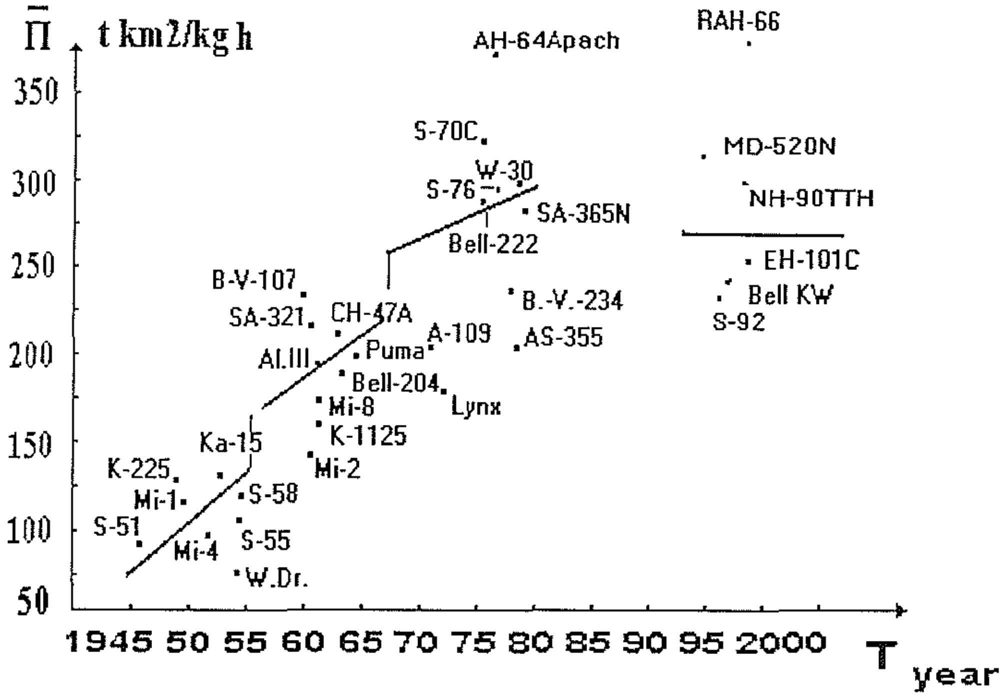


Fig. 6

Tab. 1

HELICOPTER	$\overline{M}$	p kg/m^2	q kg/h.p.	V cr.	$\overline{\Pi}$
3-d generation 1970 s					
W-30	0,44	40,3	2,5	222	307
AS-355C Super Puma	0,51	45	2,4	280	289
SA - 365N Dauphin	0,5	35,8	2,8	280	200
Bell 222	0,42	29,6	2,8	250	290,6
S-76	0,48	33,07	3,6	269	297
S-70C	0,48	43,7	2,9	268	324,2
1990 s					
AH - 64 Apach D	0,44	60,12	2,8	274	386
NH - 90 TTH	0,4	41,7	3,78	250	316,5
EH- 101 C	0,51	53,8	2,06	259	258
S - 92	0,38	47,97	2,88	259	229,
RAH - 66	0,46	69,5	2,87	260	385,2
Ka - 62	0,486	47,13	21,53	260	313,8
Bell KW (OH058D)	0,4	22,84	5,82	219	240,57
MD - 520 N	0,51	27,68	1,8	249	324,9
R - 44	0,416	13,7	4,18	209	214,4

It means, that in it parameters reflecting a perfection level of a helicopter as just the aircraft, in particular, such as cruising speed (V cr km / hour), rotor-loading (p êg/ì^2), power loading (q kg/ h.p.), over-all-payload ratio (m) are shown. Just these parameters also were analysed first of all. The results of this analysis are submitted on the diagrams, Fig.2 - 5, which reflect their development during 50 years.

Besides these parameters the operational effectiveness of helicopters by complex criteria used in practical designing was analysed. In Fig.6 changing of one of them, in particular, given reducing productivity [6] - Ï òêì^2/êg h = GuVcr L / G fuel graphically is shown., where

Gu - payload weight, Vcr - cruising speed, L - range, G fuel -fuel weight.

From the diagrams it is visible, that for last 50 years in development of helicopters three characteristic periods appropriate to three generations of helicopters are possible to allocate. These periods are differ from each other by spasmodic changing of parameters, i.e. spasmodic increasing of a level of aircraft perfection. The time interval before occurrence of the next generation is equal to approximately 10 years. However after the third generation, which has appeared in 1970 s, the jump in changing of parameters is absent, the area of a variation of their meanings for helicopters of last twenty years practically coincides with area of the third generation, tab.1.

Or else, for past 20 years the helicopter as just aircraft essentially has not changed. - Obvious delay of its development is present.

It is especially necessary to emphasise a situation with speed, so far, as it is known, development of air engineering (helicopter not the exception) goes on two basic directions: increase of speed and increase of carrying capacity.

Concerning carrying capacity it is possible to tell, that here progress is absent at all. Mi-26 constructed in 1976, and today is the heaviest helicopter which is taking place in operation. Since the 80-Th. years there is no almost mention about increase of carrying capacity as about a priority direction of development of helicopters in the special literature , i.e. in an obvious kind this requirement as if is absent, though objectively it always costs(stands) before designing. For example, in 1988-89 the information about Air Forces of USA together with firms Boeing, Lockheed and Douglas have defined necessity of development of the heavy helicopter by carrying capacity up to 22,5 tons and about works, conducted in this direction, in special literature have flown[7]. However in the literature of the next years the author did not meet the information on progress of these works, and while the promised helicopter has not appeared.

At the same time requirement of increase of speed was never removed from the agenda as one of basic for perspective rotary-wing aircraft. And since the 60-Th. years as desirable the figures compared to speeds of planes, i.e. 500, 700 and even 900 km/ p.h. were referred. And that the speed of helicopters for past 20 years practically has not changed, is a serious attribute of the crisis phenomena in designing.

Today helicopters on speed have appeared are comparable not to planes, and with modern automobiles and high-speed trains, thus conceding them in profitability and ecological acceptability (internal comfort and negative influence on an environment), already does a helicopter uncompetitiveness, for example, in the interurban communication. And if for automobiles and trains the achievement of such speeds is the certain progress, for the helicopter a twenty years' delay on these figures - an attribute of degradation. Not casually a years, and in 50-Th. years, and in 60s. Then in development of helicopters there was a jump, and the interest to the combined aircraft died away. Today this interest again is high.

Thus, as actually aircraft the helicopter for two decades has changed insignificantly. Progress is the reduction of structure weight at the expense of application of composite materials and more careful constructive working up of subsystems and separate elements, and also decrease of drag at the expense of improvement of external aerodynamics. However, the decrease of structure weight has not resulted in increase of over-all-payload ratio, since the "vacated" weight has occupied the constantly becoming complicated onboard equipment. The improvement of the onboard equipment is, as a matter of fact, main direction of development of modern helicopters, at the expense of that their reliability, safety of flight, all-wetherability, quality of making certain special tasks.

At the same time the operating effectiveness as a whole remains former, and the economic parameters are worsened.

Cost of helicopters first of all grows. For 20 years, since 1973 for 1991 the average procurement price of a helicopter has grown from $400 000 up to $10 000 000 [8], and the growth of this parameter proceeds. For example, cost of the American helicopter AH-64 Apach in 1980 was defined as $ 4 210 000 [9], and as 1983 - already in $7 200 000 [10], now - as $ 7 700 000.

Constant care of the designers and consumers of helicopters is the decrease question on the combined aircraft as to alternative to the helicopter is keen again. It is necessary to note, that this question roses always, when helicopter industry appeared in crisis: and at the end of 20-Th. - beginning of the 30-Th.

of the aircraft operation cost, but if within the limits of one generation it is possible with the help of some particular measures [F.Ex.11] to achieve relative progress in this question, as a whole from generation to generation the operating revenues grow. So for example, in 1967 cost of flight hour of the second generation helicopter S-61 (Mt.-o = 8,3 ò) made $ 234 [12], and in 1998 cost of flight hour of the third generation helicopter S-76Ñ (Mt.-o. = 5,3 ò) made already $ 669 [13].

The situation with conformity of helicopters to the ecological requirements is even more difficulty. These requirements officially are set from a beginning of the 1970s. To that time the rough development of aircraft, particularly civil, including helicopter industry, has made its coexistence with a man and as a whole with biosphere problematic. In 1971 the first restrictions on air noise [14] - from 86 up to 106 EPN dB were introduced, depending on take-off weight of the aircraft. However, in 1988 norms were reconsidered [15] in the party of some easing, approximately on 3 EPN dB, that was the compromise with opportunities of designing, but also has increased harmful influence of aircraft by an environment.

Accordingly in 1997 the new, more strong norms on noise were produced. They should enter action this year [16]. In helicopter industry the introduction of these norms has caused an alarm, since it threatens with serious restrictions on operating of helicopters and economic losses. The votes about 'necessities of balance between noise, safety of flight and economic opportunities' [f.e.17] are distributed. If to recollect, that biologically allowable noise level for the man - 55 dB, it is natural to assume, that society objectively can not allow spreading of the given mean.

In other words, given requirement of a society helicopters can not to satisfy, and, moreover, in connection with it is more strong the divergence between it and opportunities of helicopters has increased. The existing norms on engine emission now do not carry categorical character and on various parameters are exceeded by the different marks of helicopters. For example at norm of the contents of nitric oxide NOx - 40 g/kg in exhaust gases at some helicopters contains and 45, and 52, and 65 g/kg [18]. Though and at existing norms the pollution of an environment is great, and in process of increase of vehicles number the norm will have become stronger, also as well as norm on noise, about what already there is a speech in the documents ICAO [19].

Thus, the level of perfection achieved by helicopters for last twenty years, does not allow to name the newest modern helicopters as next generation, which occurrence in the near future with enthusiasm was predicted in 1980 s. The designing of helicopters for a past interval of time has not offered any essentially new revolutionary decisions which could cardinal change the basic characteristics of the aircraft, and have faster innovation character. It is possible to assert that the helicopter does not satisfy to the modern requirements of the society to technical system of the given class and the divergence with the requirements in due course is increased. Last speaks about certainly begun degradation of the aircraft, that entails decrease of demand on it and decline of all branch.

Already now unsatisfactory characteristics had an effect on scales of operating and manufacture of helicopters. In 1992-1993 began appreciable reduction of sales of helicopters, restriction of flights and even closing of helicopter airlines, in particular of urban and interurban communication [F.Ex.17,20,21].

Now in the literature the assumption of possible increase of demand for the aircraft and increase of helicopter sales. Reasons for such forecasts are increase of purchases of easy engines and hope for the opened markets of the countries former USSR and China. It is impossible to tell, that it is convincing arguments, as others, above analysed factors do not confirm optimism of these assumptions. If temporary revival caused by any circumstances of short-term action (for example, demand for military helicopters will take place in connection with a war-political situation in the world), it will carry short character and the general tendency of decrease of interest to the helicopter will not change.

In what, in opinion of the author, it is necessary to search for the reason of crisis and, accordingly, way of an output from it?

The historical and scientific and methodological analysis of designing of helicopters allows to assert, that in a basis of crisis helicopter industry the crisis of methods of designing lays. The essence of such crisis is detailed stated by the author in [3]. Briefly it can be formulated as inadequate of methods to design goal, i.e. complexity of a design task.

Modern crisis not first in a history of helicopter industry, and fourth. They always developed under one circuit: in process of accumulation of practical experience - or experience of tests (at early stages of historical development), or experience of operating of the aircraft - the goal of designing became complicated. The used methods came with it in the contradiction. Development of the helicopter was hampered, that resulted in restriction of its using, or - at early historical stages - to complete refusal of the helicopter as of unpromising idea. Then owing to the certain reasons there was a radical transformation of methods, and the development of the helicopter was advanced in steps. The general methodological approach to solving of a design task was exposed usually to transformation, i.e. essentially sight on organisation and contents of all process of designing as a whole varied. The display of the previous crises in helicopter industry is in detail described in [2].

Attributes of modern crisis of methods was planned at the end of the 70-Th. years, when the helicopter industry experienced the certain boom in connection with occurrence of the third generation. 1960 -1970s were marked by burst of designer thought, occurrence of ideas of revolutionary scale: the new types of lifting and tail rotors, new types of main rotor hubs, new materials and so on. And nevertheless, the crisis of methods was generated and in 1990s was showed by natural braking of helicopter development. Modern helicopter industry uses just the same ideas of 60 - 70-Th. years, there was the stagnation planned in it.

The research devoted to the methodological analysis of designing of systems, which is carried out now in the Cybernetics Institute of NAS of Ukraine, considers as one of itself tasks to establish the contents of methodological mistakes made by modern designing, and to determine, in what particularly discrepancy of the methodological approach to design goal consists. The situation in helicopter industry is not of inherent extremely given area of engineering. General crisis of the technoshere was planned now, in a basis of it the crisis of methodology is. In different areas of engineering the crisis is shown with a different degree of an acuteness, but it is possible to tell, that general degradation of engineering, i.e. increase of break between its opportunities and requirements of public development began.

It is explained by a complex of the socio economic and scientific and technical reasons, which at the end concentrate in the methodological approach to designing of technical system.

The designing of helicopters is one of the main objects of our research, and as preliminary conclusions it is possible to make the following remarks.

The basic tendency of historical development of process of designing - transformation it from empirical designing, inventing in research process. In due time the author established this tendency, and also the direct forms for helicopter design [2], which it is possible to consider as an initial illustration of logic of systems designing development. The helicopter - artificial system, in a basis of its idea the natural analogues do not are, and until setting up of design process was not finished as research process, that has taken place in 1930 s, the problem of creation of a helicopter did not find the solution, in difference, for example, from the plane, which, having natural analogues, was created as the efficient aircraft practically still by methods of empirical designing [2]. And every time, when in development of the helicopter the crisis was formed to leave from this condition it was possible, reducing a spontaneous - heuristic part of designing and expanding analytical, its research part.

The development of designing of helicopters, as well as any modern science, is gone to the direction of more and more integrated, complex, or system, examination of natural phenomena and public life.

According to the basic tendencies of development, it is necessary to change the modern methodological approach to

First, of more complete account of the factors forming the goal of designing, i.e. to expand definitely frameworks of the system analysis carried out during designing;

Secondly, of inclusion in structure of researched system process of designing to make it according to again generated goal;

Thirdly, of using for solving particular scientific and technical problems of designing interfering perfection of the helicopters basic characteristics, methods of the organised heuristics. In that time to use besides transforming methods [23], containing an essential elements of spontaneous and more effective, based on the morphological approach [23].

The detailed ground of the offered conclusions will be given by the author in the subsequent works.

Summarising all is higher stated, it is possible to tell, that in helicopter industry obvious crisis have developed, continuing to progress. In its basis the reasons of methodological character are. It is necessary to search output from crisis, in opinion of the author of the report, in change of the general methodological approach for a choice of the design solution.

REFERENCES

1 .Диксон Д.. Проектирование систем. - М.:Мир,1969,- 440 с. (J.Dixon. Design engineering. -N.Y.-London,1966).

2.Болиева Т.Ч... Развитие методов проектирования вертолетов .Дисс.на соискание степени к.т.н. - М.:ИИЕТ АН СССР.-1987.(T.Ch.Bolieva. Razvitie metodov proektirovanija vertoljotov).

3.Bolieva T.Ch.. Characteristic Fceature of the Goal and Method Used for Helicopter Design as an Object of System Analysis. - 24- th European Rotorcraft Forum,
Marseilles, France - 1998.

4.Гаспарский В..Праксеолигический анализ проектно-конструкторских разработок.- М.:Мир.1978.-172 с (W.Gasparsky . Kriterium metoda wyboru rozwazania technicznego w ujenciu prakseolometrycznym . Warsawa, 1970).

5. Дитрих Я. Проектирование и конструирование. Системный подход – М.:Мир, 1981.

6. Тищенко М.Н., Некрасов А.В., Радин А.С.. Вертолеты: Выбор параметров при проектировании. - М.:Машиностроение,- 1976.

7. Designe consepts for an advanced cargo rotorcraft./Shrage D.P.,Costello M.F., Mittleider D.N.// AIAA Paper.- 1988,-N4496, - P.1-10.

8. Перспективы развития зарубежных ВКЛА (обзор иностранной печати)./ сост. Е.И.Ружицкий, И.Г.Косарева. - М.:ОНТИ ЦАГИ. (TSAGI).

9. Brown says no major changes in Advances Attack Helicopter /Def.Space Bus.Daily. - 1980. - 109, N33. - P.246.

10. Flying the Hughes AH-64 Apache. / Lambert Mark // Interavia. - 1983. - 38,N 8, - P.833-836.

11. Reducing helicopter operating costs./Olson John R. //Vertiflite. - 1993.- 39, N1.- P.10-16.

12. Advent of the economic helicopter./Austin R.J.// Flight International.- 1967.- 92, N3045,- P.107-III.

13. S-76C.Powerful performe./ Graup. //Flight Int.- 1998.-154,N4642, - P.47-51.

14. ICAO/ 8.16.2.(1).- Montreal, 1971.

15. ICAO/ 8.16.2.(1).- Montreal, 1988.

16. JAR OPS 3. - 1997.

17. Helicopters for buisness./Sarsfield K.// Flight Int.-1998.- 154.N4641,- P.130-131.

18. ICAO/8.16.2.(2).- 1993.

19. ICAO. Circular 270-AT/111.- Montreal, 1997.

20. Groupe aerospatiale 1991: croissance de 16% du chiffre d' affaires 213 millionce de francs de benefice// Deron. et astronaut.- 1992. N2. - P.52.

21. Ventes d'helicopteres: la reprise se fait affendre// Air et cosmos/ Aviat. mag. - 1992. - N1382.- P.27-28.

22. Healthy helicopter market forcast /Proctor Paul// Aviation Week and Sp.Techn.- 996.- 144,N14.- P.42.

23. Одрин В.М. Метод морфологического анализа технических систем.- М.:ВНИИТИ,1989.- 310 с.

24. Jane's all the World' s aircraft. - Lnd. - 1985- 1998.

25. ICAO. Digest of statistics. - 1970-1997.

26."Flight","Aviation Week", "Aeroplane", "Air et cosmos" and other periodoca l editions.

SESSION
TESTING Flight Mechan 66

P6

(Abstract submitted for consideration for presentation at the 25th European Rotorcraft Forum, September 14-16, 1999, Rome, Italy)

Flight Evaluation of an Adaptive Neural Network Flight Controller of an Uninhabited Helicopter

A. J. Calise, J.V.R. Prasad,
Georgia Institute of Technology
School of Aerospace Engineering
Atlanta, GA 30332, USA

J. E. Corban
Guided Systems Technologies, Inc.
P.O. Box 1453
McDonough, GA 30253, USA

Abstract

This paper presents recent results from our experimental flight controls research program, whose main focus is aimed at flight evaluation of a neural network based adaptive flight controller. A description is given of the uninhabited helicopter flight controls research testbed and associated avionics package. This is followed by a detailed description of our adaptive neural network based flight control architecture for attitude and trajectory control. Next, a description of the integration of the inertial measurement unit (IMU) with the onboard global positioning system (GPS) is presented. The paper concludes with results from our simulation and flight experiments.

Introduction

Traditional methods of flight control design consist of gain scheduling many linear point designs across the flight envelope using a high fidelity dynamic simulation. Continued reliance on these (albeit proven) methods contributes greatly to the expense associated with producing a new flight vehicle, and also limits achievable system performance. This is especially true when the flight system dynamics exhibit strong nonlinearities or are uncertain.

As an alternative, nonlinear techniques such as feedback linearization and dynamic inversion have been developed. Despite the power of these techniques, they fail to produce truly significant economic or performance-based improvements due to continued dependence on precise knowledge of the system dynamics. Research at Georgia Tech has recently demonstrated a direct neural network based adaptive control architecture that can compensate for unknown plant nonlinearities in a feedback linearizing setting. These neural network based controllers look very much like traditional adaptive control elements. Neural networks are viewed as highly nonlinear control elements that offer distinct advantage over more conventional linear paramter adaptive controller in achieving system performance.

In order to experimentally validate our research, and to support other activities in the area of autonomous flight vehicles research, we have developed an experimental flight controls research facility using a Yamaha R-50 uninhabited helicopter. The objective of this paper is to present an overview of our neural network based adaptive control methodology, describe the integration of IMU with the onboard GPS, and then summarize some of our flight test results.

Uninhabited Aerial Vehicle Research Facility

The UAVRF was initiated in June of 1997. This facility is dedicated to flight testing of advanced control algorithms on model helicopters. It presently contains two Yamaha model R-50 helicopters, each having 12 HP liquid cooled engines, a payload capability of 44 pounds and endurance of approximately 30 minutes.

The on-board system consists of a 200 Mhz Pentium based flight control processor with 32 Mb RAM and an R-1 integrated avionics system. The list of on-board sensors includes: BEI motion pack 3-axis gyro and accelerometer package, NovTel RT-2 differential GPS with 2 cm accuracy, 3-axis magnetometer, and 8 channel ultrasonic ranging system. A wireless modem digital data link is used to provide a two way communication link with a mission cntrol ground station. In addition, an on-board multiplexer switch allows a human safety pilot to engage the system, and to over-ride the flight control system in the event of an emergency. The control actuators consists of 3 linear servos for cyclic and collective control, and 2 rotary servos for yaw and throttle control. The UAVRF also houses two 300Mhz PCs that are used for hardware in the loop simulation, which permits accurate simulation and hardware testing of each mission prior to flight test.

Simulation Model

A nonlinear simulation model of the R-50 helicopter has been developed based on the math model given in Ref. 1. The model of Ref. 1 includes, in addition to a six degrees-of-freedom fuselage, a first-order representation of main rotor flapping and quasi-steady representation of main and tail rotor inflows. This model has been modified to include a simplified control rotor model developed in Ref. 2, a pilot's radio controller model and simplified engine and RPM governor models. Initial estimates of the aerodynamic data are adjusted using flight test data.

Adaptive Nonlinear Flight Control

This section presents an overview of the control system design. The interested reader is referred to Refs. 3 through 7 for more background on the subject approach to direct adaptive control of nonlinear systems, additional design details, derivation of the neural network update law, and a proof of stability.

The controller can be configured in each of the three rotational axes independently as either a rate or attitude command system. Handling qualities are prescribed by the use of a command filter which serves both to limit the input rate, and as a model for desired response. Specification of "good" handling qualities is not yet well defined for unmanned helicopters, and is the subject of future research. Figure 1 presents a block diagram of the control system architecture for the longitudinal channel when this channel is configured for rate command. The lateral and directional channels are identical in form. The construction of this block diagram is discussed in the following.

The design starts with an approximate linear model of the rotational dynamics of the helicopter which is to be inverted at a nominal operating condition.

$$\dot{\omega} = A_1 x_1 + A_2 \omega + B\delta \qquad (1)$$

In Equation (1), $\omega = [p, q, r]^T$ is the vector of angular rates about the body fixed axes [3], and A_1, A_2 and B represent matrices of the aerodynamic stability and control derivatives at the nominal operating point, respectively. The vector of standard helicopter control inputs, δ, is employed. It contains lateral and longitudinal cyclic pitch, δ_{LAT} and δ_{LON}, main rotor collective pitch, δ_{COL}, and tail rotor collective pitch, δ_{DIR}. In this formulation, the main rotor collective control position is treated as an additional translational state (i.e. it is assumed relatively slow), so that $x_1 = [u, v, w, \delta_{COL}]^T$.

The methodology assumes the 'pseudo control' vector, U, to be of the form

$$U = U_c + \dot{\omega}_c - U_{AD} \qquad (2)$$

The elements of U_C are the outputs of independent linear controllers, each operating on its corresponding error signal. The linear controller designs are used to specify the tracking error transients in each channel. Typically the transient is designed to be fast relative to the dynamics of the command filter but slow relative to the actuator dynamics. In the example of Figure 1, the pitch channel is configured as a rate command system. Integral action is added to provide for attitude retention giving it the designation Rate Command, Attitude Hold (RCAH).

In some piloting tasks, one may prefer instead an attitude command system. In such case the linear controller for the pitch channel example is designed as

$$U_c = K_p(\theta_c - \theta) + K_d(\dot{\theta}_c - \dot{\theta}) \qquad (3)$$

where θ denotes the pitch Euler angle. In this case a second order command filter is employed, and the second, rather than the first, time derivative of the command is fed forward. An outer loop trajectory controller can be set up with the attitude command system performing the inner loop function and using a methodology similar to Ref. 8.

Returning to the case of rate commands in all three axes, the commanded angular accelerations are constructed by the command filters as

$$\dot{\omega}_c = [\dot{p}_c, \dot{q}_c, \dot{r}_c]^T \qquad (4)$$

The left hand side of Equation (1) is set equal to the desired angular accelerations, the elements of which (in the case of rate command systems) are identically the pseudo controls constructed for each channel. The result, after substituting using (2) and (4), is then solved for the vector of helicopter controls

$$\delta = B^{-1}\{U - A_1 x - A_2 \omega\} \qquad (5)$$

Note that the linear model being inverted is only an approximation to the true helicopter dynamics, and that inversion error will therefore result in each channel. This inversion error can be expressed as a function of the states and pseudo controls.

The neural network output, U_{AD}, serves to adaptively cancel these inversion errors through on-line learning. The learning is accomplished by a simple weight update rule derived from Lyapunov theory, thus assuring the stability of the closed-loop system. The subject design employs a multilayer neural network with sigmoidal activation functions in the hidden layer. A neural network of this type is capable of approximating any smooth function to any desired accuracy, provided the number of hidden layer neurons is sufficiently large. Inputs to the neural network in each channel are taken as the rotational states, pitch and roll Euler angles, and the corresponding pseudo control.

Control System Implementation

For the purpose of real-time simulation and flight test, the control system formulation presented in the previous section has been coded in the C programming language. It runs in real-time in double precision with an update rate of 100 Hz on a 200 MHz Pentium-based Single Board Computer (SBC). The SBC is interfaced via shared memory to a previously developed commercial-grade flight control system known as the R1. The R1 provides for collection and management of sensor data, hardware and software interface to both the actuators and the pilot, and management of all telemetry links to a ground control station. For the current program, the R1 flight control system with SBC has been integrated on a Yamaha R-50 industrial unmanned helicopter, which is a 150 pound gross weight production vehicle designed for agricultural spraying. The result is a very capable unmanned helicopter testbed. Features of the R1 flight control system and its sensor suite are discussed in the following.

The R1 system is designed to support the integration of independent functional modules in order to accommodate a wide variety of research needs. Up to four Motorola 68332 processors communicate using high speed serial data transmissions (Motorola Queued Serial Peripheral Interface, QSPI). There are two 16 channel 12 bit analog to digital conversion boards interfaced to the primary 68332 via the QSPI. The four 68332s provide a total of 64 digital input/output channels with precision timing control functions for tasks such as generation and reading of pulse code modulated signals.

The R1 card cage also houses driver circuitry for an eight channel ultrasonic ranging system. This system is used to measure range to the ground over prepared surfaces during take-off and landing sequences. The card cage also accommodates a spread spectrum digital data link and a Rockwell MicroTracker differential GPS receiver (3-5 meter accurate sensing of position in differential mode with updates once per second). The original sensor suite included an Attitude and Heading Reference System (AHRS) based on the Systron Donner Motion Pak coupled with a Honeywell 3-axis magnetometer. The Motion Pak is a 3-axis cluster of solid state rate sensors and linear accelerometers. The AHRS provides measurements of angular rates, linear accelerations, and magnetic field strength from which magnetic heading and the pitch and roll attitude angles are derived.

Alternate sensor suite modules include an upgrade of the GPS receiver to either the Novatel RT-20 or the RT-2 (20 and 2 cm accurate positioning solutions respectively in differential mode with carrier phase lock and 5 Hz update rates), and substitution of the AHRS with a complete GPS-aided inertial navigation solution. Planned flight tests will employ the inertial navigation solution aided by the RT-2. The system has a 12 channel interface to standard pulse width modulated radio control equipment for the pilot interface, and sensors for measuring the rotational rates, temperatures, etc. The system operates on a 12 to 28V DC input power supply.

Hardware-in-the-Loop Testing

Figure 2 presents a block diagram of the real-time, hardware-in-the-loop test facility developed to prepare for flight evaluations of the controller. The right half of the figure represents the flight control system hardware and software described in the previous section. The left half of the figure represents elements introduced in order to conduct simulation studies. Only the Flight System elements depicted on the right are employed when flying the aircraft. In such case the actuator movements result in the true dynamic response of the aircraft. This response is characterized by the sensor suite and digitized at regular sampling rates. This sensor data is used for feedback control, and the traditional helicopter control deflections are computed.

Simulation and Flight Test Results

Preliminary flight test results for the pitch channel RCAH are presented in Figures 3 and 4 for the cases without and with adaptive neural network, respectively. It is clear from these figures command tracking is significantly improved with the adaptive neural net controller. The final paper will include additional flight test results for attitude and trajectory command tracking.

Summary

Design of a helicopter control system using a combination of feedback linearization and a neural network-based technique for on-line adaptation is presented. Hardware and software implementation of the controller on an unmanned helicopter testbed is then discussed. Simulation as well as flight test evaluation results are presented to illustrate the ability of the neural network controller to perform to specification in a real application environment. The final paper will include a detailed description of the IMU integration with the onboard GPS and simulation and flight test results of the attitude and trajectory controller.

References

1. Heffley, Robert K., "Minimum-Complexity Helicopter Simulation Math Model," NASA CR 177476, April 1988.
2. Perhinschi, M. and Prasad, J.V.R., "A Simulation Model of an Autonomous Helicopter," Proceedings of the RPV/UAV Systems 13th Bristol International Conference, April 1998.
3. Kim, B.S., Calise, A.J., "Nonlinear Flight Control Using Neural Networks," AIAA J. of Guidance, Control, and Dynamics, Vol. 20, No. 1, 1997.
4. Leitner, J., Calise, A.J. and Prasad, J.V.R., "Analysis of Adaptive Neural Networks for Helicopter Flight Control," J. of Guidance, Control, and Dynamics, Vol. 20, No. 5, Sept. – Oct., 1997.
5. Calise, A. J. and R. T. Rysdyk, "Nonlinear Adaptive Flight Control Using Neural Networks," IEEE Control Systems Magazine, 1998.

6. McFarland, M. B., and A. J. Calise, "Multilayer Neural Networks and Adaptive Nonlinear Control of Agile Anti-Air Missiles", Presented at the August 1997 AIAA Guidance, Navigation and Control Conference, Paper No. 97-3540.
7. Corbanm E., Calise, A.J. and Prasad, J.V.R., "Implementation of Adaptive Nonlinear Control for Flight Test on an Unmanned Helicopter," CDC, December 1998.
8. Prasad, J.V.R. and Lipp, A.M., "Synthesis of a Helicopter Nonlinear Flight Controller Using Approximate Model Inversion," Mathematical and Compter Modelling, Vol. 18, No. 3-4, pp. 89-100, 1993.

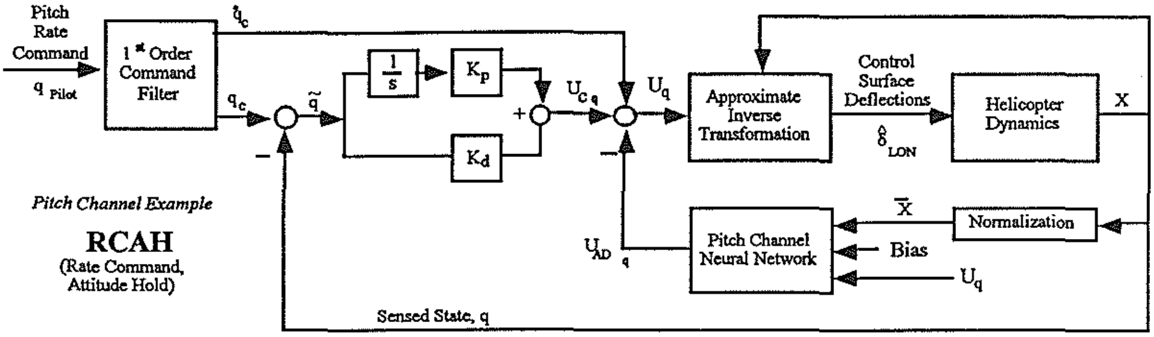


Figure 1. Block diagram of Rate Command, Attitude Hold System for Pitch Channel.

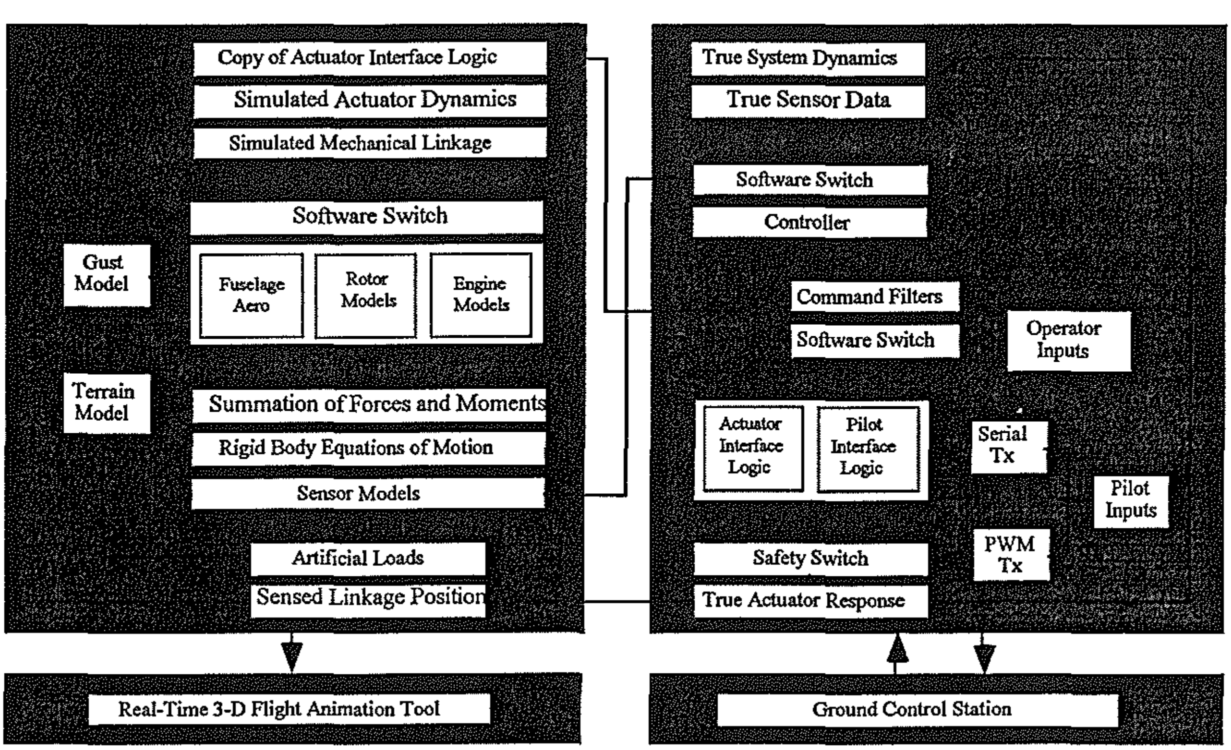


Figure 2. Joint GST/Ga Tech Real-Time Hardware-in-the-Loop Simulation Facility

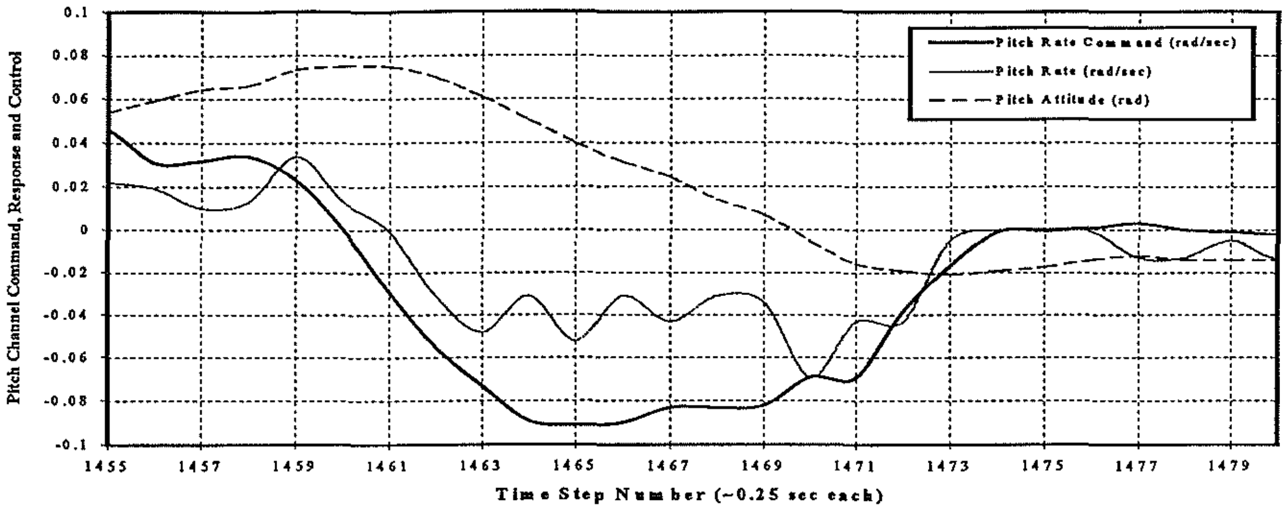


Figure 3. Preliminary Flight Test Results for Pitch Channel RCAH, No Adaptation

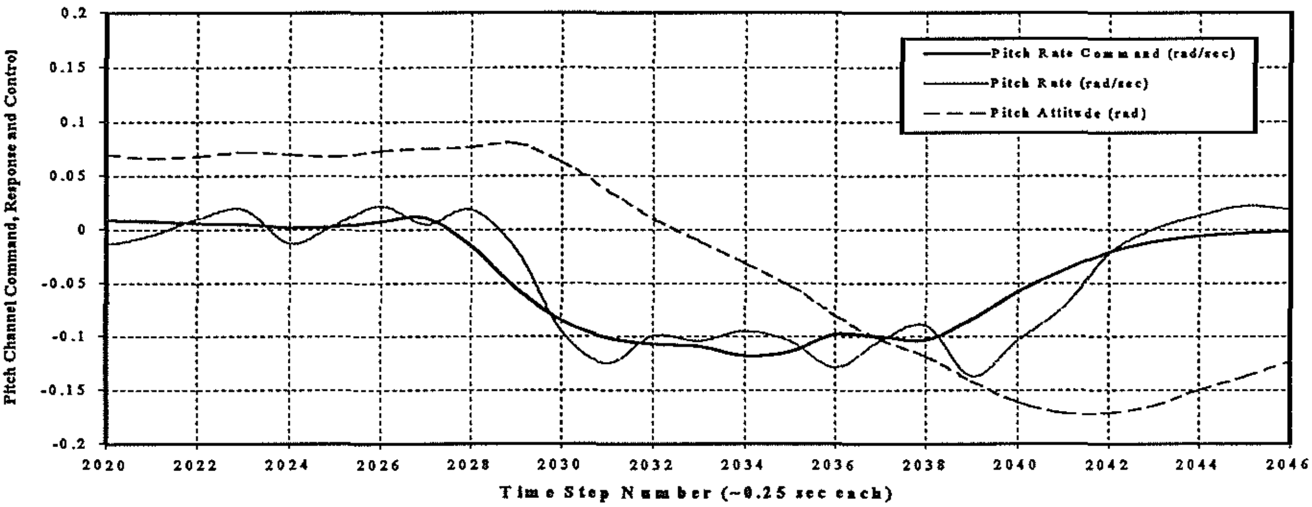


Figure 4. Preliminary Flight Test Results for Pitch Channel RCAH, with Neural Net Controller.